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Root zone construction affects hybrid bermudagrass (*C. dactylon* x *C. transvaalensis*) responses to simulated traffic

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Abstract

Few studies have directly compared the types of root zones used for athletic fields. A two-year field study was conducted from 2012-2013 at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to compare the performance of four root zones: a silt loam root zone, a sand-based root zone constructed to United States Golf Association (USGA) specifications, a sand-based root zone constructed to ASTM International (ASTM) specifications, and a sand-cap root zone (CAP) consisting of silt loam capped with 15 cm of sand that conformed to USGA particle size specifications. Hybrid bermudagrass (*C. dactylon* x *C. transvaalensis*, cv. 'Tifway') was established over all root zones. In addition to the bermudagrass treatments, two different synthetic turf surfaces varying in fiber type and infill ratio were included for comparison. All treatments were subjected to 30 simulated traffic events each autumn at rates of 0, 3 or 10 simulated traffic events per week in a split-plot design. Differences were only detected in percent green cover only for traffic rate in 2012. In 2013, bermudagrass on silt loam was reduced to 50% cover after ~10 simulated traffic events, compared to ~18 simulated traffic events on USGA and ASTM sand-based root zones. Surface hardness varied between treatments and years of the study; however, at no time did any surface exceed surface hardness thresholds associated with head injury (200 Gmax). Despite the loss of hybrid bermudagrass cover from the repeated simulated traffic events, few differences in surface hardness were detected between synthetic turf and hybrid bermudagrass plots in this study, regardless of root zone.

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Keywords: synthetic turf, bermudagrass, athletic fields, surface hardness

1. Introduction

Athletic field root zones provide a medium to support turfgrass growth under diverse weather conditions and foot traffic [1]. The two most common types of athletic field root zones are engineered sand-based systems and native soils [2]. Native soil root zones containing primarily silt and clay can easily become compacted, limiting oxygen available for turfgrass root growth [1]. Sand-based root zones are less susceptible to these phenomena but can be both time consuming and costly to construct [3]. Consequently, native soil root zones are most common on high school and municipal fields while sand-based root zones are used regularly at professional and collegiate stadiums [4].

Sand-based athletic fields are often constructed to meet the United States Golf Association (USGA) specifications for sand-based putting greens [2]. The USGA sand-based putting green specifications require a mixture of sand particle sizes to maximize both macro- and microporosity. Sand-based root zones constructed to USGA specifications must offer 35-55% total porosity, as well as 15-30% air-filled porosity and 15-25% capillary porosity [5]. The American Society of Testing and Materials (ASTM International; ASTM) developed an alternative guide for constructing sand-based athletic field root zones [6]. Root zones constructed according to ASTM guidelines are designed to provide 35-45% total porosity and be more resistant to compaction than finer root zones [6]. However, the ASTM guide allows sand-based root zones to contain more fine gravel (3.4 to 4.75 mm diameter particles) and total fine sized particles (< 0.05 mm diameter particles) than those constructed to USGA specifications with the hopes of added stability for footing. Research comparing the performance of root zones constructed to

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USGA and ASTM guidelines is limited. A side-by-side comparison of these systems would benefit individuals constructing or renovating sand-based athletic field root zones.

Information comparing the performance of sand-based athletic fields to those established on native soil is also limited. Bell and Holmes [7] found sand-based root zones used for soccer enhanced the wear tolerance of perennial ryegrass (*Lolium perenne* L.) and provided greater traction than native soil. While Bell and Holmes [7] investigated four sand-based root zones, none were constructed to meet USGA or ASTM specification nor were they subjected to the rigors of American football traffic. Native soil root zones contain relatively high amounts of silt and clay making them susceptible to compaction during periods of excessive foot traffic; these root zones also retain more moisture, which can compromise surface stability [8]. Henderson et al. [9] reported heavily trafficked athletic field root zones should contain > 90% sand to avoid water content determining the strength of the root zone. This finding supported work by Baker and Isaac [10] on trafficked athletic fields under wet conditions. Excessive soil water in native soil root zones has even forced simulated traffic research projects to be with-held for fear of excessive wear due to weather conditions [11].

A sand-cap root zone of 15 cm of sand and peat mixture over an existing native soil provides turf managers a less costly alternative to engineered sand-based systems (typically 30 cm in depth over gravel and drainage tile). The Sports Turf Managers Association [12] reported that a 20 to 30 cm deep sand-based root zone (placed over a gravel bed) for high school football cost $577,930. These systems can be constructed all at once or sand can be added through topdressing over time [13]. Sand-cap root zones should have additional drainage tiles [13]. Topdressing to create a sand-cap over time improved the surface stability characteristics of both Kentucky bluegrass (*Poa pratensis* L.) and bermudagrass (*Cynodon dactylon* L.) athletic fields [14; 15]. On golf course putting greens, Oppold [16] reported that 99% of the compaction was confined to the top 10 cm of the root zone; thus athletic fields constructed with a sand-cap may be well suited to withstand the rigors of foot traffic associated with sports. However, Oppold [16] noted that creating a layer of sand (5 to 10 cm) over native soil may cause water infiltration issues throughout the profile because once the water passes through the sand layer it will slow at the sand to soil interface, thus the reason Kowalewski et al. [13] suggests adding additional drainage tiles.

Thus, the objective of this research was to compare the response of natural and artificial turf on five different root zones under varying intensities of simulated athletic traffic. The hypothesis is the artificial turf and the sand-based root zones will perform better than the root zones containing native soil.

2. Materials and Methods

A two-year field study was conducted from 2012-2013 at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to compare the performance of four sand- and soil-based athletic field root zones and one crushed stone root zone with two different synthetic turf surfaces. Root zones were constructed as 4.6 m x 9.1 m plots from 2010 to 2011. Root zones evaluated in this research included: 1) a Sequatchie silt loam (fine-loamy, siliceous, semiactive, thermic humic Hapludult) measuring 6.2 in soil pH and 2.1% in organic matter content; 2) Sequatchie silt loam capped with 15 cm of sand-peat (CAP). Sand used for this CAP confirmed to USGA particle size specifications for root zone construction [5]; 3) a sand-based root zone constructed to USGA specifications; and 4) a sand-based root zone constructed to ASTM guidelines. All sands were blended with 20% by volume with sphagnum peat moss. 5) All synthetic turf plots consisted of self-contained plots with 15 cm base of washed aggregate (25 to 2.4 mm) capped with 5 cm of fine aggregate (9.5 to 0.3 mm) over flat drainage tile. Each plot was separated with a 4.6 m alley.

All natural turf root zones were sprigged with 'Tifway' hybrid bermudagrass (the most popular turfgrass for the growing conditions) on 3 Jun 2011. A complete fertilizer (18 N – 1.3 P – 15 K) was applied at 25 kg N ha^{-1} on 2 Jun 2011. From July 2011 thru 15 Sept. 2011, plots were fertilized biweekly with urea (46 N – 0 P – 0 K) at 49 kg N ha^{-1}; plots received monthly applications of urea (46 N – 0 P – 0 K) at 49 kg N ha^{-1} from April to September of 2012 and 2013. Plots were individually irrigated immediately following urea applications. All plots were mowed at 2.2 cm three times per week with a reel mower (TriKing 1900D; Jacobsen. Charlotte, NC) from April through October. Clippings were allowed to return to the surface while mowing. Each spring, all hybrid bermudagrass plots received an application of oxadiazon (Ronstar 50WP; Bayer Environmental Sciences. Research Triangle Park, NC) at 3360 g ai ha^{-1} on 23 February 2012 and 25 February 2013 to prevent weeds. Oxadiazon was applied with a CO_2 powered boom sprayer calibrated to deliver 281 L ha^{-1} using 8002 flat-fan nozzles (TeeJet; Spraying Systems Co. Roswell, GA). Plots received ~2.5 cm of irrigation within 24 hours of oxadiazon treatment. Overhead irrigation was applied to supplement rainfall throughout the duration of the study.

Synthetic turf playing surfaces were installed over these gravel bases on 12 April 2011.While two synthetic turf playing surfaces comprised of horseshoe shape monofilament fibers were included, Fiber Type 1, containing short nylon fibers (thatch) in addition to the monofilament fibers (5.1 cm pile height), and Fiber Type 2, monofilament fibers (5.7 cm pile height) without those nylon fibers (AstroTurf USA, Dalton, GA 30721). All fibers were extruded from polyethylene yarn and coated with polyurethane. Synthetic turf surfaces in the experiment were infilled with mixtures of sand (2 mm to 0.05 mm) and crumb rubber particles (2 mm to 0.15 mm) on 21 April 2011 at either 12.2 kg of crumb rubber to 4.88 kg of sand m^{-2} for plots containing Fiber type 1 and thatch or 13.7 kg of crumb rubber to 4.88 kg of sand m^{-2} for Fiber type 2. The ratios were selected based on manufacturer specifications (AstroTurf USA, personal communication 2011). Synthetic turf plots were groomed and crumb rubber was loosened with a synthetic turf groomer (TurfCare TCA1400; SMG Equipment. Auburn, WA) on 16 July 2012 and 15 July 2013.

Simulated traffic was applied using a CADY traffic simulator constructed similar to Henderson et al. [17]. Two passes with the CADY traffic simulator impart the same number of cleat marks (667 m^{-2}) found between the hashmarks (at the 40-yard line) after one National Football League game [17]. In this study, simulated traffic was applied at three rates: 0 simulated events wk^{-1}, 3 simulated events wk^{-1} (i.e., six passes with the CADY for ten weeks), and 10 simulated events wk^{-1} (i.e., 20 passes with the CADY for three weeks) until 30 simulated events (i.e., 60 passes with the CADY) had been applied to all plots. Traffic was applied from 6 Aug. to 12 Oct. 2012 and 5 Aug. to 11 Oct. 2013. In 2013, simulated traffic was applied to both hybrid bermudagrass and synthetic turf surfaces that had not been subjected to traffic the previous year.

Performance of both synthetic and hybrid bermudagrass plots was quantified by measuring changes in green cover (however percent green cover for synthetic plots never dropped below 95% so that data is not presented) and surface hardness following simulated traffic. Measurements of turfgrass cover provide the best evaluation of traffic tolerance [18]. Percent green cover of each plot was quantified at the beginning of the study and after every five simulated traffic events using digital images analysis (DIA) as described in Thoms et al. [19]. Digital images were collected with a Canon camera (G5, Canon Inc., Japan) capable of capturing 5 million pixels per image. Total image size in this study was 307,200 pixels. SigmaScan Pro software (v. 5.0, SPSS Inc., Chicago, IL) used image pixelation measurements to calculate green cover according the methods of Richardson et al. [20].

Surface hardness data were collected on all plots before and after each rate of simulated traffic had been applied each year. Surface hardness was measured using the F-355 Apparatus A (F355, Triax 2000, Playground Clearing House, Toronto, CA) equipped with a 9.1 kg missile and accelerometer dropped from a height of 610 mm [21]. This device's output was selected for presentation as the data it generates has been associated with human cadaver's likelihood of suffering traumatic brain injuries [22]. Gurdjian et al. [23] reported human cadavers impacting car steering wheels at GMAX above 200 were likely to suffer a brain injury. The F355 measures surface hardness as Gmax, a unit-less number representing the ratio of maximum deceleration of the missile upon impact, in units of gravities (G), relative to the acceleration due to gravity [21]. Similar to Brosnan et al. [24], F355 data reported were the average readings of the second and third drop in the same location within a plot to follow the ASTM protocol. Three F355 values were collected to characterize the surface hardness in each plot. Volumetric soil water content was measured on each hybrid bermudagrass plot using a hand-held time domain reflectometry (TDR) probe (TDR 300, Spectrum Technologies, East Plainfield, IL) equipped with 5 cm tines inserted into the soil vertically when surface hardness data were collected. Synthetic turf infill depth was measured using a three-prong surface depth gauge (3 prong surface depth gauge; Canadian Playground Advisory Inc., Toronto, Canada). Means for volumetric soil water content and infill depth were generated using seven subsamples per plot.

The experiment was designed as a randomized complete block split plot with three replications and repeated in time during 2012 and 2013. The whole plot factor was athletic field type (i.e. hybrid bermudagrass, ASTM; Fiber Type 1, crushed aggregate) while the split plot factor was simulated traffic rate (0, 3, or 10 events wk^{-1}). Percent green cover and surface hardness data were subjected to analysis of variance in SAS (v. 9.1; SAS Institute Inc., Cary, NC). Significant year-by-treatment interactions were detected and therefore data were presented by year. Percent green cover data were analyzed using non-linear regression techniques in GraphPad Prism 6 for Windows (GraphPad Software, San Diego, CA.). A sums of squares reduction F-test was conducted to compare sums of squares from a global model (all treatments shared the same parameter estimates) to a cumulative model where unique parameter estimates were calculated for each treatment. Regression curves were used to calculate the number of simulated traffic events required for each root zone to be reduced to 50% green cover ($Events_{50}$ values). Fisher's protected least significant difference test was used to separate surface hardness means at the $\alpha = 0.05$ level. Pearson's correlation coefficients were calculated to determine relationships between volumetric soil water content and surface hardness.

3. Results and Discussion

Percent green cover varied due to athletic field type in 2013 and traffic rate in both years; however, no athletic field type-by-traffic intensity interactions were detected in either year. In 2012, athletic field type had no effect on hybrid bermudagrass green cover ($P \leq 0.53$). $Events_{50}$ values for the CAP, ASTM, silt loam, and USGA root zones were 7.1, 7.9, 8.3, and 8.4 simulated traffic events, respectively.

Image 1. Digital examples of hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) during the application of 30 simulated traffic events in the summer and fall of 2012 and 2013 with the image on the left having 25% green cover and the image to the right having 50% green cover as determined by digital image analysis in Knoxville, TN.

In 2013, significant differences in hybrid bermudagrass cover were detected among root zones ($P \leq 0.0078$; Table 1). $Events_{50}$ values indicate that hybrid bermudagrass established on silt loam was reduced to 50% cover after 10.3 simulated traffic events, compared to 18.3 and 18.6 simulated traffic events for the USGA and ASTM root zones, respectively. The CAP root zone ranked intermediate, requiring 11.8 simulated traffic events to be reduced to 50% cover.

Table 1. Number of simulated traffic events to reach 50% green cover of hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) grown on four different root zones[1] during the application of 30 simulated traffic events in the summer and fall of 2012 and 2013 in Knoxville, TN. Standard error of the mean (SEM) values are presented as a means of statistical comparison.

Simulated Traffic Events to 50% Green Cover		
Root zone type	2012 (+/- SEM)	2013 (+/- SEM)
ASTM sand-based root zone	7.9 (+/-0.4)	18.6 (+/- 0.05)
Sand cap root zone	7.1 (+/-0.4)	11.8 (+/- 0.06)
Native soil root zone	8.3 (+/- 0.4)	10.3 (+/- 0.08)
USGA sand-based root zone	8.4 (+/- 0.4)	18.3 (+/- 0.04)

[1] Root zones consisted of: a sand-based root zone constructed to American Society of Testing and Materials (ASTM) guidelines that was blended with 20% sphagnum peat moss (by volume); a sand-based root zone constructed to United States Golf Association (USGA) specifications that was blended with 20% sphagnum peat moss (by volume); a native-soil root zone comprised of Sequatchie silt loam; a sand-cap system consisting of Sequatchie silt loam capped with 15 cm of sand blended with 20% sphagnum peat moss (by volume). Sand used for this cap confirmed to USGA particle size specifications for root zone construction.

Differences in green cover retention each year may be related to rainfall as our site received an additional 20 cm of rainfall (141 cm) in 2013 compared to 2012. Improved green cover retention on sand-based USGA and ASTM root zones in 2013 (compared to the silt loam) may be the result of increased drainage potential; however, infiltration and saturated hydraulic conductivity were not measured in this experiment. Soil moisture readings (Tables 1 and 2 footnotes) were higher in 2013 than 2012 for every surface except the USGA root zone at the conclusion of 30 simulated traffic events, supporting the theory of additional precipitation in 2013.

In both years significant differences in green cover loss were detected between low and high traffic intensities ($P \leq 0.0011$; Table 2). In 2012, plots subjected to the low traffic intensity were reduced to 50% green cover after 9.4 simulated traffic events compared to only 6.6 simulated traffic events for the high traffic intensity. This difference was more pronounced in 2013 as plots receiving the low traffic rate required 27.4 simulated traffic events to be reduced to 50% green cover compared to 9.9 simulated traffic events for the higher traffic rate.

Table 2. Number of simulated traffic events to reach 50% green cover of hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) grown on four different root zones during the application of 30 simulated traffic events in 2012 and 2013 in Knoxville, TN. Standard error mean (SEM) values are presented as a means of statistical comparison.

Simulated Traffic Events to 50% Green Cover		
Simulated traffic rate	2012 (+/- SEM)	2013 (+/- SEM)
Low traffic rate (3x events/wk)	6.6 (+/- 0.09)	9.9 (+/- 0.03)
High traffic rate (10x events/wk)	9.4 (+/- 0.01)	27.4 (+/- 0.04)

Surface hardness. In 2012, the USGA root zone had greater surface hardness (122 Gmax) than all other treatments tested except the silt loam root zone (114 Gmax; $P \leq 0.0028$; Table 3). Only the USGA root zone measured higher in surface hardness than Fiber Type 1 over crushed aggregate (106 Gmax) or Fiber Type 2 over crushed aggregate (105 Gmax). No other differences in surface hardness were detected among athletic field systems in 2012.

Table 3. Surface hardness values following application of 30 simulated traffic events with the CADY traffic simulator to hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) established on four different root zones and two different synthetic turf surfaces varying in fiber type during 2012 in Knoxville, TN.

Athletic Field Type	Surface Hardness (Gmax[1])
Hybrid bermudagrass, ASTM[2]	102[3]
Hybrid bermudagrass, CAP	104
Hybrid bermudagrass, Silt loam soil	114
Hybrid bermudagrass, USGA	122
Fiber Type 2, Crushed aggregate	105[4]

Fiber Type 1, Crushed aggregate	106
$LSD_{0.05}$	13.2

[1] Surface hardness was measured with a F-355 Apparatus A device equipped with a 9.1 kg missile, drop height of 440 mm, and accelerometer in units of Gmax. Each sample was dropped in the same location three times with the average of the second and third drop equaling a sample. Means represented the average of three samples from each plot.
[2] Root zone construction and abbreviations consisted of: a sand-based root zone constructed to American Society of Testing and Materials (ASTM) guidelines that was blended with 20% sphagnum peat moss (by volume); a sand-based root zone constructed to United States Golf Association (USGA) specifications that was blended with 20% sphagnum peat moss (by volume); a native-soil root zone comprised of Sequatchie silt loam (fine-loamy, siliceous, semiactive, thermic humic Hapludult) measuring 6.2 in soil pH and 2.1% in organic matter content; a sand-cap system (CAP) consisting of Sequatchie silt loam capped with 15 cm of sand blended with 20% sphagnum peat moss (by volume). Sand used for this cap confirmed to USGA particle size specifications for root zone construction.
[3] Volumetric soil moisture content was measured on each hybrid bermudagrass plot using a time domain reflectometry (TDR) probe (TDR 300, Spectrum Technologies, East Plainfield, IL) equipped with 5 cm tines when surface hardness data were collected, TDR measurements for each root zone is as follows: ASTM (19%), CAP (19%), Native (30%), and USGA (17%).
[4] Synthetic turf infill depth was measured at the same time as surface hardness measurements using a three prong surface depth gauge (3 prong surface depth gauge; Canadian Playground Advisory Inc., Toronto, Canada). Infill depth measurements are as follows for each synthetic surface: Horseshoe fiber (32 mm) and Horseshoe fiber with thatch (32 mm).

In 2013, athletic field type-by-traffic rate interactions were detected in surface hardness data (Table 2). The highest surface hardness value occurred on hybrid bermudagrass; hybrid bermudagrass on a USGA root zone subjected to 10 events wk^{-1} (116 Gmax) was greater than Fiber Type 1 on crushed aggregate subjected to 10 events wk^{-1} or hybrid bermudagrass on an ASTM root zone (99 Gmax for either traffic rate), CAP root zone subjected to 10 events wk^{-1} (87 Gmax), and silt loam root zone subjected to 3 events wk^{-1} (81 Gmax). Overall, surface hardness values on synthetic turf ranged from 100 to 114 Gmax regardless of fiber type or traffic rate. Surface hardness values were considerably lower on hybrid bermudagrass subjected to 10 events wk^{-1} than synthetic turf in 2013 for native soil (81 Gmax). Regardless of athletic field type or traffic rate, surface hardness values on hybrid bermudagrass ranged from 81 to 116 Gmax in 2013 (Table 2). None of the hybrid bermudagrass or synthetic turf surfaces tested exceeded the 200 Gmax limit that has been associated with increased likelihood of traumatic brain injury at any time [21].

Table 4. Surface hardness values following application of 30 simulated traffic events with the Cady traffic simulator to hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) established on four different root zones and two different synthetic turf surfaces varying in fiber type. Traffic was applied at two rates during 2013 in Knoxville, TN.

Traffic Rate (events wk^{-1})	Athletic Field Type[1]	Surface Hardness[2] (Gmax)
3	Hybrid bermudagrass, ASTM	99[3]
	Hybrid bermudagrass, CAP	113
	Hybrid bermudagrass, Silt loam Soil	113
	Hybrid bermudagrass, USGA	113
	Fiber Type 1, Crushed aggregate	113[4]
	Fiber Type 2, Crushed aggregate	105
10	Hybrid bermudagrass, ASTM	99
	Hybrid bermudagrass, CAP	87
	Hybrid bermudagrass, Silt loam soil	81
	Hybrid bermudagrass, USGA	116
	Fiber Type 2, Crushed aggregate	114
	Fiber Type 1, Crushed aggregate	100
	$LSD_{0.05}$	14.4

[1] Root zone construction and abbreviations consisted of: a sand-based root zone constructed to American Society of Testing and Materials (ASTM) guidelines that was blended with 20% sphagnum peat moss (by volume); a sand-based root zone constructed to United States Golf Association (USGA) specifications that was blended with 20% sphagnum peat moss (by volume); a native-soil root zone comprised of Sequatchie silt loam (fine-loamy, siliceous, semiactive, thermic humic Hapludult) measuring 6.2 in soil pH and 2.1% in organic matter content; a sand-cap system (CAP) consisting of Sequatchie silt loam capped with 15 cm of sand blended with 20% sphagnum peat moss (by volume). Sand used for this cap confirmed to USGA particle size specifications for root zone construction.
[2] Surface hardness was measured with a F-355 Apparatus A device equipped with a 9.1 kg missile, drop height of 440 mm, and accelerometer in units of Gmax. Each sample was dropped in the same location three times with the average of the second and third drop equaling a sample. Means represented the average of three samples from each plot.
[3] Volumetric soil moisture content was also measured on each hybrid bermudagrass plot using a time domain reflectometry (TDR) probe (TDR 300, Spectrum Technologies, East Plainfield, IL) equipped with 5 cm tines when surface hardness data were collected, TDR measurements for each root zone is as follows for 3 simulated events per week: ASTM (22%), CAP (19%), Native (38%), and USGA (15%) and for 10 simulated events per week: ASTM (20%), CAP (26%), Native (40%), and USGA (18%) .
[4] Synthetic turf infill depth was measured at the same time as surface hardness measurements using a three prong surface depth gauge (3 prong surface depth gauge; Canadian Playground Advisory Inc., Toronto, Canada). Infill depth measurements are as follows for each synthetic surface after 3 simulated events per week: Horseshoe fiber (30 mm) and Horseshoe fiber with thatch (31 mm) and for 10 simulated events per week: Horseshoe fiber (33 mm) and Horseshoe fiber with thatch (33 mm).

In 2013, surface hardness were less for the ASTM root zone (99 Gmax) the other three hybrid bermudagrass root zones (113 Gmax for Cap, silt loam, and USGA) when subjected to simulated traffic at 3 events wk^{-1}. However, when subjected to the more intense rate of traffic (10 events wk^{-1}), the ASTM and USGA root zones yielded higher surface hardness values than the silt loam or CAP root zone. Interestingly, surface hardness values for the silt loam and CAP root zones were higher when subjected simulated traffic at three events wk^{-1} compared to ten event wk^{-1}. This may be related to the fact that volumetric soil water content was lower (3 to 8%) on the silt loam and CAP root zones subjected to 3 events wk^{-1} rather than ten events wk^{-1} (Table 2 footnote). Surface hardness has been significantly correlated with volumetric soil water content that as soil water content decreases surface hardness increases [25].

Low but significant correlations were detected between total soil water content and surface hardness on the natural turf plots. Total soil water content ($r=-0.27$, $P \leq 0.001$). This relationship implies that surface hardness was greater on natural turf surfaces with lower soil moisture content. These results are similar to previous findings with the Clegg Impact Soil Tester and soil moisture content [25] that have been reported as soil moisture content increases surface hardness will decrease.

Differences in percent green cover due to root zone construction were only detected in a single year of this two-year study. Hybrid bermudagrass maintained on sand-based root zones (i.e, USGA, ASTM) retained higher percent green cover than a silt loam root zone following exposure to simulated traffic. Variable rainfall between years suggests that future research should investigate effects of root zone infiltration and saturated hydraulic conductivity on hybrid bermudagrass traffic tolerance. Few differences in surface hardness were detected between synthetic turf and hybrid bermudagrass in this study, at no time did surface hardness exceed thresholds associated with increased likelihood of traumatic brain injury [26]. Our study was limited in that synthetic surfaces were not subjected to regular maintenance practices such as grooming [27]. These practices may have affected surface hardness values in response to simulated traffic. Future research should explore effects of grooming on the hardness of synthetic turf surfaces similar to those used herein.

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